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Development and Testing of the CRYOTSU Flight Experiment

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Abstract. This paper describes the development and ground testing of the CRYOTSU thermal management flight experiment. CRYOTSU incorporates three cryogenic temperature experiments and one ambient temperature experiment into a Hitchhiker (HH) Get Away Special (GAS) Canister that is currently scheduled to fly on STS-95 in October 1998. The cryogenic experiments consist of a nitrogen triple-point cryogenic thermal storage unit (CTSU), a nitrogen cryogenic capillary pumped loop (CCPL), and a hydrogen gas-gap cryogenic thermal switch (CTSW). The ambient experiment is a carbon-fiber core, paraffin-filled thermal storage unit. Test results of integrated flight canister testing are provided herein for the CTSU and CCPL experiments. Pre-integration laboratory test results are provided for the CTSW. Design information and test results for the ambient experiment are not included.

INTRODUCTION

Owing to the increased utilization of cryogenic instruments and IR sensors in space, thermal engineers need to have a much wider range of cryogenic thermal management tools at their disposal to meet design requirements. The three principal thermal management areas in which cryogenic devices need to be developed and flight-qualified are cryogenic thermal storage, cryogenic thermal transport, and cryogenic thermal switching.

Cryogenic thermal storage devices are needed for components with highly variable heat loads, in order to minimize the size, weight, and power dissipation of cryocoolers. Cryogenic thermal transport systems are needed for situations where the cryogenic cooling source must be located remotely from the cooled component. An example would be trying to cool a sensor on a 2-axis gimbal with a spacecraft-mounted cooler. Cryogenic thermal switches are needed to minimize the "off-cooler" parasitic loads in redundantly cooled (35 K and below) systems.

Given those needs, which have both military and civilian system underpinnings, the CRYOTSU flight experiment was conceived. CRYOTSU integrates the following four experiments -- a nitrogen triple-point cryogenic thermal storage unit (CTSU), a nitrogen cryogenic capillary pumped loop (CCPL), a hydrogen gas-gap cryogenic thermal switch (CTSW), and an ambient thermal storage device -- into a Hitchhiker (HH) Get Away Special (GAS) Canister mounted to the side-wall of the Space Shuttle bay.

The CRYOTSU mission, planned for STS-95 in October 1998, is the fifth flight of this unique HH-GAS Canister, which is referred to as the Cryogenic Test Bed (CTB). The CTB, which houses five Hughes 7044H tactical cryocoolers and associated control electronics, was developed jointly by NASA/GSFC and AFRL to enable experimenters to carry out cryogenic experiments in space. This paper describes the design and testing of the three cryogenic experiments aboard the CRYOTSU flight experiment.

The paper is organized as follows. First, background information is provided on the principal cryogenic thermal management areas under investigation. Next, the design and test results of the three CRYOTSU cryogenic thermal management devices are described and analyzed. Lastly, a summary is provided which describes how the work described herein fits into a wider-ranging initiative to incorporate new cryogenic technologies into space systems.

BACKGROUND

This section provides background information and rationale for development of thermal management tools in the areas of cryogenic thermal storage, cryogenic thermal transport, and cryogenic thermal switching.

Cryogenic Thermal Storage

The sources of heat flow into a cryogenic IR instrument are electrical dissipation and environmental parasitics. While the parasitic load remains nearly constant, the electrical dissipation varies depending on whether the detector is "on" or "off". For systems with low-to-medium sized arrays, the electrical dissipation is small, and these small arrays are usually left "on" continuously. However, for larger arrays, electrical dissipation is dominant. For these systems, weight and power can be reduced by duty-cycling the detector, resulting in a lower average load. By adding a cryogenic thermal storage unit (CTSU) to "store cooling" during detector off-periods, the cryocooler can be sized for the average instead of the peak load, resulting in a lighter, lower power cooler. Systems with gimbaled optics, that periodically view earth and deep space, also can benefit from load averaging. Figure 1 illustrates the concept.

There are two cryogenic thermal storage options: sensible heat storage and latent (phase change) heat storage. The simplest approach is to absorb peak heat loads using a sensible heat device such as a block of metal. While simple in design, a sensible heat device is not as weight efficient or as thermally stable as a phase change material (PCM) device. In fact, a PCM device can be 10 to 50 times lighter than the sensible heat device. Using either CTSU option on a system with significant load variations can result in system savings of over 100 times the mass of the CTSU.

Cryogenic Thermal Transport

In most cryogenic systems, the cooling source and cooled component are coupled with a flexible conductive link (FCL) like an aluminum strap or copper braid. In most cases, this approach works well. However, as the transport length and heat load are increased, the FCL becomes heavy and inefficient. In these cases, the preferred thermal coupling device is the fluid circulator. Fluid circulators can be single or two-phase devices, with mechanical or capillary pumping mechanisms. Two-phase fluid circulators include the cryogenic capillary pumped loop (CCPL), the cryogenic loop heat pipe (CLHP), and cryogenic heat pipes. Single-phase fluid circulators include the cryogenic pumped gas loop (CPGL). Single and two-phase fluid circulators have been used numerous times as coupling devices in space cryogenic systems (Bugby, 1998). Figure 2 illustrates the essential elements of single and two-phase cryogenic fluid circulator systems.

As indicated above, the weight advantage of cryogenic fluid circulators becomes apparent as the heat load and transport length are increased. Other advantages include inherent diode action, greater integration flexibility, vibration isolation, lower parasitics, higher conductance, more convenient placement of coolers for ambient heat dissipation, and others. Some system architectures, such as gimbaled optics with spacecraft-mounted coolers, could not be implemented without fluid circulators like the CCPL, CLHP, or CPGL.

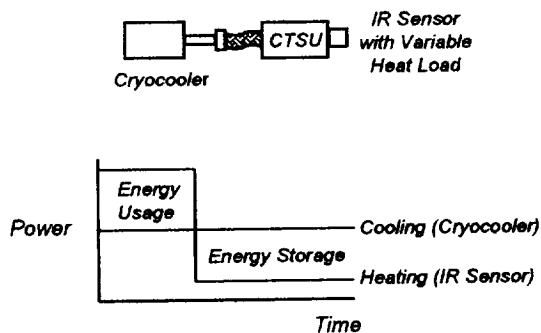


FIGURE 1. Cryogenic Thermal Storage System.

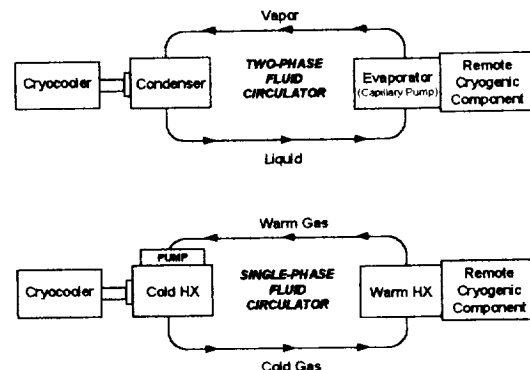


FIGURE 2. Cryogenic Fluid Circulator Systems.

Cryogenic Thermal Switching

For the near future, all low risk (non-experiment) cryocooler space applications will probably require redundancy due to the lack of statistical life test data on the mechanical, long-life cryocoolers. Cryocooler redundancy can significantly increase the cooling loads by adding parasitics from the non-operating or "off" cryocooler. For typical space cryocoolers, this additional heat load is about 0.5 W at 60 K. This situation can be handled in two ways.

If the cryocooler has sufficient capacity, the simplest approach is to absorb this extra load into the operating budget of the "on" cryocooler. However, if margins are tight and/or the cryocooler has a small capacity relative to this load, a cryogenic thermal switch (CTSW) is needed. A properly designed CTSW has the capability to thermally isolate the "off-cooler" from the instrument and reduce parasitic heat loads by at least 3 to 5 times. It should also be mentioned that as the instrument operating temperature decreases, cryocooler power efficiency becomes increasingly poorer and it becomes even more important to minimize parasitic heat loads. Thus, at 10 K, where a typical cryocooler capacity may only be 0.1 W, a thermal switching device may be essential for system feasibility. Figure 3 illustrates a redundantly cooled dual CTSW system

FLIGHT EXPERIMENT DESIGN AND TESTING

This section addresses the design and testing of the three CRYOTSU cryogenic experiments -- CTSU, CCPL, and CTSW -- and their overall design and integration into the flight canister. The test data in this section will be a mix of pre-integration component-level laboratory testing and pre-flight ground testing of the integrated system.

Overview of the Flight Experiment

The CRYOTSU Flight Experiment packages three cryogenic experiments and one ambient experiment into a Hitchhiker (HH) Get Away Special (GAS) Canister. This canister is known as the Cryogenic Test Bed (CTB) and it provides five Hughes 7044H cryocoolers and associated electronics for carrying out cryogenic experiments in space. Each CTB split-Stirling cryocooler provides 3.5 W of cooling at 80 K. Previous flights of the CTB were CRYOHP, CRYOTP, and CRYOFD (Beam, 1992, Glaister, 1995, and Thienel, 1998).

Due to the 100 W that each cryocooler dissipates, the CTB cannot run indefinitely with five (or even four) coolers turned on. So, the phase change upper end plate (PCUEP) was added both as an experiment and as part of the thermal control system. This device, with 600 W-hrs of energy storage capacity at 318 K, will extend the operating time of the experiment. Two axially-grooved ammonia heat pipes transport a portion of the waste heat to the PCM device. The layout of the CRYOTSU flight experiment is provided in Figure 4.

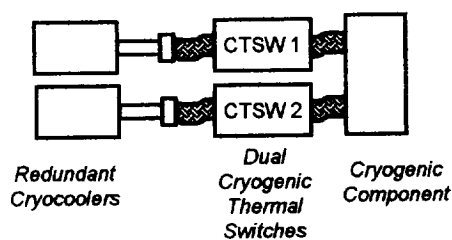


FIGURE 3. Dual CTSW System.

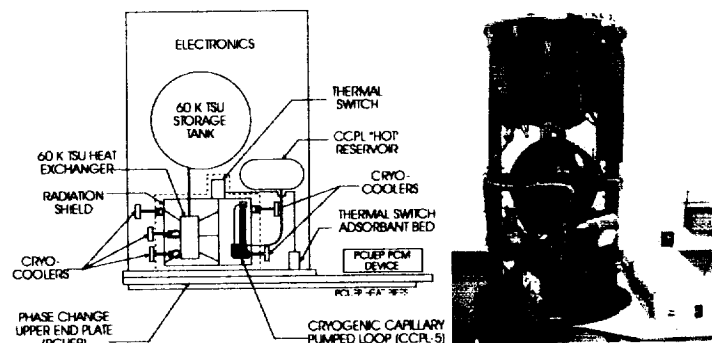


FIGURE 4. Layout of the CRYOTSU Flight Experiment.

Cryogenic Thermal Storage Unit (CTSU)

The principal CTSU flight components are shown in Figure 5. The unit is a dual-volume system with a 140 cc cylindrical beryllium heat exchanger and a 16,760 cc spherical stainless steel storage tank. The flight system was filled to 0.61 MPa (88.5 psi) with nitrogen, which represents a charge of 0.118 kg. Since the vapor pressure of nitrogen at its triple-point is 0.012 MPa (1.8 psi), only 0.115 kg is available for phase change. With a liquid density of 870 kg/m^3 and a solid density of 1020 kg/m^3 at the triple-point (63.15 K), the heat exchanger will be 95% filled with nitrogen when liquid and 80% filled with nitrogen when solid. With a nitrogen heat of melting of 25,700 J/kg, the theoretical energy storage capacity of the flight CTSU is 2960 J.

Figure 6 illustrates the CTSU heat exchanger (HX). The HX was constructed of two halves into which were drilled a large number of 2.8 mm ID, non-through holes. To join the two halves and obtain a hermetic seal, a method known as Hot Isostatic Pressure (HIP) bonding was used. In this process, the two halves are pressed against each other at high pressure and temperature. This process bonds the beryllium surfaces without any bond-line or seam. Figure 6 illustrates the seamless HX and the bimetallic (Ti-SS) fill tube which was brazed into the side of the unit using an aluminum-based braze material. Figure 7 is a block diagram of the essential elements of the CTSU flight system. One of these elements is a cooled radiation shield (RS) within which the CTSU HX is suspended by low-conductance kevlar cables. Figure 8 illustrates the CTSU HX/RS subsystem.

The CTSU test data reported herein represents that taken during pre-flight ground testing of the integrated system. A component-level laboratory test program, which indicated the CTSU flight unit would perform acceptably, was carried out beforehand (Bugby, 1998).

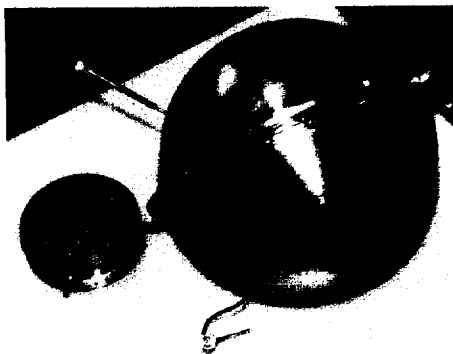


FIGURE 5. CTSU HX and Storage Tank.

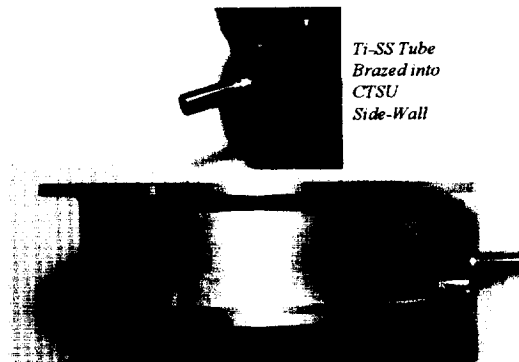


FIGURE 6. CTSU Heat Exchanger (HX).

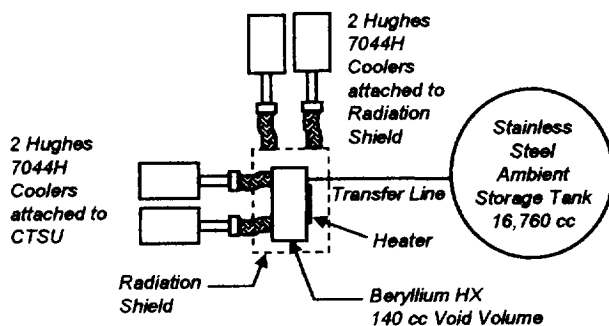


FIGURE 7. CTSU Flight Cooling System.



FIGURE 8. CTSU HX Suspended in RS by Kevlar Cables.

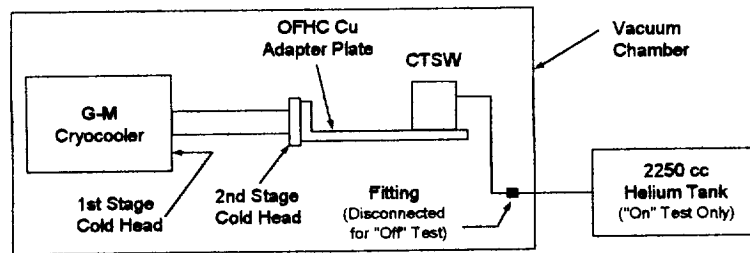


Figure 18. Cryogenic Thermal Switch Laboratory Test Set-Up.

SUMMARY

This paper has described the design, operation, flight configuration, and ground test results of three advanced cryogenic integration devices for future space-based cryogenic systems. The cryogenic thermal storage unit (CTSU), cryogenic capillary pumped loop (CCPL), and cryogenic thermal switch (CTSW) were each successfully ground tested in preparation for an upcoming flight experiment in late October 1998. These three devices are important parts of an AFRL-sponsored initiative to incorporate new and enabling cryogenic technologies into space systems. This initiative, dubbed the Integrated Cryogenic Bus (ICB), endeavors to combine a range of cryogenic integration solutions to meet future requirements. Overall, this paper has attempted to elucidate the features and benefits of the three aforementioned ICB devices to be flight-tested during the CRYOTSU Flight Experiment.

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